The discovery of a giant debris arc in the Coma Cluster

Neil Trentham

Institute for Astronomy, University of Hawaii

2680 Woodlawn Drive, Honolulu HI 96822, U. S. A.

and

Bahram Mobasher

Astrophysics Group

Blackett Laboratory, Imperial College

Prince Consort Road, London SW7 2BZ, U. K.

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ABSTRACT

We present the discovery a giant low surface-brightness arc, of length ~ 80 kpc in the Coma Cluster. The arc consists of a diffuse luminous matrix with surface-brightness $\mu_B < 26.5$ mag arcsec^{-2} and a number of embedded condensations. It is not associated with any giant galaxy in Coma in particular; neither does it have the properties of a gravitational arc. We argue that a fast interaction between the nearby barred S0 galaxy IC 4026 and either IC 4041 or RB 110 is the most natural explanation for the origin of the arc.

Key words: galaxies: clusters: individual: Coma $-$ galaxies: interactions

1 INTRODUCTION

Interactions between galaxies are an important mechanism driving galaxy evolution. One aspect of this process that has been investigated in detail is the interactions between galaxies in clusters. This is because the galaxy densities in clusters is high, and so observations lead to a robust statistical description of the galaxy population there, at least at bright magnitudes (see e.g. Binggeli 1994).

Present-day clusters have high observed velocity dispersions (~ 1000 km s^{-1}), close to the virial values. This means that interactions between galaxies in clusters normally occur at high relative encounter velocities, which in turn means that the energy transfer between the two galaxies is small (Binney & Tremaine 1987). One might therefore expect violent interactions between galaxies like those described by Toomre & Toomre (1972) to be rare in clusters.

However, observations tell us that galaxies in clusters **are** undergoing significant evolutionary changes. In particular, the blue Butcher-Oemler (1978, 1984) galaxies seen in clusters at redshifts $z > 0.2$, are not seen at $z = 0$. A number of explanations of this have been hypothesized (e.g. Lavery & Henry 1988, Kauffmann 1995), based on the notion that interactions may indeed play an important role if they occur during the early stages of cluster formation before virialization, when the galaxy velocities are small. More recently, Moore et al. (1996) have investigated the effects of galaxy harassment i.e. the cumulative effect large numbers of high velocity encounters in the cluster gravitational potential well. Their models show that harassment can simulatenously account for disappearance of the Butcher-Oemler galaxies and the properties of dwarf elliptical galaxies seen in large number in low-redshift clusters.

So interactions may indeed be important in shaping galaxies in clusters. We might therefore expect to see features like low surface-brightness tidal tails and merger debris (Barnes & Hernquist 1992) in clusters, particularly in young clusters that are not dynamically relaxed, and in clusters which are merging with other clusters. Indeed, Moore et al. (1996)

describe the existence of giant debris arcs in clusters as a natural consequence of their harassment models.

We now report the discovery of such an arc or tail, of length ~ 80 kpc, in the Coma cluster ($z = 0.023$), located 13.4 arcminutes from the cluster center. Such features were difficult to find previously because of their very low surface brightnesses and the large angular sizes of nearby clusters like Coma, and the consequent need to survey large areas at depth. The new large-format CCDs that are used on large telescopes now permit such surveys to be made, and the arc we describe here was independently discovered in two such surveys. It is perhaps not surprising that such a feature should be found in Coma, where the absence of a cooling flow (Stewart et al. 1984) and the existence of two large central galaxies of approximately equal optical luminosity are suggestive that Coma might be the result of a recent merger between two smaller clusters. If this is true, it will not be a relaxed system today.

2 OBSERVATIONS

The arc (see Fig. 1) was discovered in a deep two-color (B and R) survey of Coma (Trentham 1997), conducted using a thinned backside-illuminated Tektronix 2048 X 2048 CCD at the f/10 Cassegrain focus of the University of Hawaii 2.24 m telescope on Mauna Kea. The exposure times for this survey were 35 minutes in the $B-$band and 25 minutes in $R-$band, using Mould filters, with a median seeing of $0.75''$ FWHM. The arc was confirmed independently in the data from a second survey, using the 4.2 m William Herschel Telescope on La Plama. It has very low surface-brightness (< 26.5 mag arcsec^{-2} in the $B-$band), but is clearly visible above the sky background (see Figure 1c). The center of the arc is at $(\alpha(1950),\delta(1950)) = (12^{\rm h}58^{\rm m}5.3^{\rm s}, 28^\circ 19' 52.52'')$. The arc is about $3'$ long, has a radius of approximately $40''$, and is located at about $13.4'$ from the cD galaxy NGC 4874 in the direction N62.9°E and $7.05'$ from the other supergiant Coma cluster galaxy NGC 4889 in

the direction N43.2°E (at the distance of the Coma cluster one arcminute corresponds to 26 kpc). No radio or X-ray source is known at the location of the arc.

Figure 1c shows that the arc consists of a diffuse luminous matrix and a number of embedded condensations. The arc looks approximately circular with radius $40''$, but in fact is poorly fit by a circle or ellipse; the mean residual from the best-fit circle to the five brightest condensations that are not background galaxies is about $10''$. The photometric properties of the arc are shown in Figure 2. The brightest objects in the arc are labelled, and their colours and magnitudes are presented in Table 1. The relative height of the B and R lines in Figure 2 gives a good estimate of the colour of each object. Red objects are mostly background; a giant elliptical galaxy in Coma has $B - R = 1.9$ (Coleman et al. 1980) so objects redder than this are probably background galaxies.

In Figure 2, we also display the surface-brightness detection thresholds required to find the arc. Only the more recent CCD surveys approach the faint limits required to detect the arc. The 1σ sky noise of the UH 2.24 m data was 28.3 B mag arcsec^{-2}. The total area of the UH 2.24 m survey was 674 arcminutes, and this was the only such feature found – such objects are presumably either very short-lived or very rare, even in clusters like Coma that we suspect to be unrelaxed. Previous photographic surveys of Coma (e.g. Thompson & Gregory 1993) routinely surveyed areas much larger than this, but were not deep enough to find features like this arc. Previous deep CCD surveys (e.g. Bernstein et al. 1995) easily reached sky noise levels this low, but did not cover sufficient area to find these features either. It is the combination of area and depth that allow the new large-format CCD surveys like the UH 2.24 m and the Herschel 4.2 m surveys to detect objects such as this.

The arc may continue beyond the limits shown in Figure 2, but its surface-brightness would then have to be less than the sky noise in this region. Figure 2 also shows that the luminous matrix is visible above the sky over the entire length of the arc; while this may in part be due to the way we have geometrically defined the arc, Figure 1c confirms that there is indeed a substantial amount of flux seen between the condensations. The maximum

surface brightness of the matrix is 26.5 mag arcsec^{-2} in the $B-$band; this corresponds to object P.

The arc is not gravitational, as suggested by the following observations. Firstly, the arc is resolved in the radial direction, having a thickness of up to $10''$, about ten times the seeing. Gravitational arcs, on the other hand, are normally radially unresolved. Secondly, many of the embedded objects are resolved and do not have a colour distribution consistent with them all being part of a single background galaxy. Finally, for an Einstein ring with a lens at the distance of Coma, the angular radius θ must satisfy the inequality $\theta < 9.6 \left(\frac{M}{10^{11}\mathrm{M}_{\odot}}\right)^{0.5}$ arcseconds, where M is the enclosed mass. The observed angular radius of about $40''$ would then require an enclosed mass of at least $2 \times 10^{12}\mathrm{M}_{\odot}$. This is unreasonably large for the region enclosed by the arc, which is $13.4'$ from the cluster center, and in which there is no optical emission. In any case, the Einstein ring interpretation is probably incorrect, as the arc is so poorly fit by a circle.

3 DISCUSSION

The arc is similar in appearance to the tidal features described by Barnes & Hernquist (1992); the condensations therein might then be dwarf galaxies in formation. However, unlike the tails in the simulations, the arc here is not clearly associated with any giant galaxy in particular. Table 2 lists the nearby galaxies; their locations can be seen in Figure 1(b). If the arc is debris from an interaction between galaxies, the galaxies involved must therefore have traveled some distance from the arc.

The large distances between the arc and the nearest galaxies suggest that if the arc results from interaction, the encounter velocities of the galaxies involved must be high. The galaxy harassment simulations of Moore et al. (1996) may therefore offer some additional clues to the origin of the arc. If the harassment models provide a reasonable prescription for these observations i.e. the arc is debris from a fast encounter between two galaxies, we ought to be able to identify both a harassed and harassing galaxy. We refer to the galaxy providing

the material for the arc as the harassed galaxy, and the one with which it has experienced a recent fast encounter as the harassing galaxy. The present-day 3-D velocity dispersion of Coma is 1010 km s^{-1} (Zabuloff et al. 1990) so that the 1-D velocity dispersion in the plane of the sky is ~ 0.3 degree/Gyr = 20 arcmin/Gyr ($H_0 = 75$ km s^{-1} kpc^{-1}). Therefore one might expect the harassed galaxy to be within a few arcminutes of the arc. The barred S0 galaxy, IC 4026 is far and away the closest giant galaxy in Coma on the concave side of the arc, and so is the best candidate for being the harassed galaxy. It is $2.0'$ from the center of curvature of the arc in the direction S60°E. It is an attractive candidate for the harassed galaxy because fast encounters can create bars in the harassed galaxy (Moore et al. 1996). Furthermore, IC 4026 has a similar color to most of the objects in the arc, as is predicted by the harassment models. A few objects (e.g. E and I) have slightly bluer colours; this is probably due to small amounts of recent star formation in the debris. If this interpretation is correct, then the time since harassment is approximately $0.1 \left(\frac{V_{ah}}{500\,\mathrm{kms}^{-1}}\right)^{-1}$ Gyr, where V_{ah} is the present-epoch relative velocity of the arc and IC 4026 in the plane of the sky. The most natural place to search for the harassing galaxy is the opposite side of the arc from IC 4026 in a direction opposite to S60°E i.e. N60°W. Candidate galaxies include IC 4041 ($5.1'$ from IC 4026 in the direction N53°W) and RB 110 (S0 galaxy, $4.2'$ from IC 4026 in the direction N62°W). From Table 2, the projected component of the encounter velocity perpendicular to the plane of the sky is ~ 1100 km/s for IC 4041 and ~ 700 km/s for RB 110; these numbers are consistent with a fast encounter interpretation. For these galaxies, the time since harassment is approximately $0.5 \left(\frac{d}{10'}\right)\left(\frac{V_{gh}}{500\,\mathrm{kms}^{-1}}\right)^{-1}$ Gyr, where V_{gh} is the present-epoch relative velocity of the harassing galaxy and IC 4026 in the plane of the sky and d is the angular separation of the two galaxies, as stated above. For a value of V_{gh} of twice the 1-D velocity dispersion of Coma, the time since harassment would be 0.22 Gyr and 0.18 Gyr for IC 4041 and RB 110, respectively. If the encounter velocity is higher (Moore et al. consider encounter velocities as high as 1500 km s^{-1}), these times would be shorter, and the arc would be younger. While we have argued, mostly on *a posteriori* grounds, that

a fast interaction is the likeliest explanation for the arc, it should also be recgnized that lower velocity hyperbolic interactions could also produce such a feature. Given the high observed velocity dispersion of Coma, it is perhaps unlikely that such an interaction would occur between cluster members (again on *a posteriori* grounds). But the arc, if produced in a low-velocity encounter, would be dynamically cold, and the parent galaxies could then lie well away from it in the plane of the sky, further than any of the galaxies listed in Table 2.

Comparison between this arc and either the tails simulated by Barnes & Hernquist, or the arcs simulated by Moore et al. therefore does reveal some similarities. The main difference in both cases seems to be that the arc is not clearly associated with any galaxy in particular, although the timescales involved suggest that the fast encounter hypothesis is plausible. As more simulations are carried out, in particular with differing harassed galaxy types, encounter velocities and geometries, and local environments, it will hopefully become clear whether this feature of the arc that we see can be readily explained. What determines the position of the center of curvature of the arc (it is coincident with neither IC 4026 or the cluster center) is another problem that is not readily addressed by the existing simulations. Measuring the arc redshift would be another a useful test of our interpretation, as well as a possible means of identifying the harassed and harassing galaxes (the arc redshift should be close to, preferably intermediate between, the redshifts of the harased and harassing galaxies). However, it is not at present feasible to do this, even with the largest telescopes, as the arc is too faint. Redshifts of the brightest two or three objects within the arc may be obtainable, but we cannot be sure that these are at the same redshift as the diffuse material.

The colours of the objects in the arc (see Table 1), suggest very little ongoing star formation there, as most objects are red, with $B-R$ of 1.4 to 1.6 (similar to IC 4026). This suggests that most of the material in the arc is stellar debris from the harassed galaxy, and that there is probably very little gas in the arc; this is perhaps not surprising as the harassed galaxy is a S0 galaxy – these are normally gas-poor. Objects C and H are very blue, and

may be globular clusters in formation. However, they are very faint ($M_B = -10$), and will fade even more as they get older.

Throughout this discussion we have assumed that the diffuse material in the arc lies in the Coma Cluster. This is not rigorously proven (only a spectroscopic redshift for the diffuse material would do that), and we assess the alternative possibilites here. Some of the condensations (like A, B, and D) are probably background galaxies, as they have colours typical of old stellar populations at $z \approx 0.2$. The arc is probably not associated with these because the colour of the diffuse material is significantly bluer than the colours of these galaxies (this might be caused by ongoing star formation, but it would then have to be spread over a feature 0.8 Mpc in size). A more serious potential worry is that the arc is in fact a foreground object that happens to lie in front of the Coma Cluster. Then its size would not be as big as we claim. However, no object similar to this has been seen in any of the very deep wide-field surveys of the field and nearby groups of galaxies undertaken by the authors (ten times the area of this survey have been surveyed down to $R = 26.5$ mag arcsec^2). This, combined with the concordance between the colours of the arc and many Coma Cluster galaxies, suggests that the most straightforward interpretation of the arc at this stage is that it belongs to the Coma Cluster.

To summarize, we have discovered a giant debris arc in Coma and regard fast encounters between nearby galaxies as the likeliest explanation of its properties, although the comparison between the observed properties of the arc and existing simulations raise a number of new questions. New simulations with input parameters derived from the observed parameters of the galaxies identified here will also be useful in further assessing the nature of the arc.

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FIGURE CAPTIONS

Figure 1. **(a)** Region of the Coma cluster surveyed by Trentham (1997); the survey covered $\sim$ 97% of the area shown here. This image comes from the Palomar Sky Survey. It is 26 arcminutes square. The box indicates the location of the smaller area displayed in (b). Here, as in all three images, North is up and East is to the left; **(b)** A 6.5 arcminute square region containing the arc, and showing clearly the giant galaxies in the vicinity of the arc. This image is from our B-band UH 2.24 m data. The six large galaxies in the frame, clockwise from the upper right are IC 4026, RB 100, IC 4042, IC 4041, RB 110, and IC 4040. All are S0 galaxies, except IC 4040, which is a very disturbed Sdm galaxy. The box shows the location of the smaller area displayed in (c); **(c)** The B-band image of the arc, from our UH 2.24 m data. The image appears somewhat granular; this contrast is best to show the low-surface-brightness arc against the sky background.

Figure 2. **(a)** The variation in $B-$band and $R-$band flux density within a $3.0''$ diameter circular aperture, with position along the arc. The photometry presented here is from our sky-subtracted UH 2.24 m data. The seeing was 0.75 arcseconds in B and 0.76 arcseconds in R. The distance along the arc (the ordinate parameter) was computed as follows. The n^{th} point P_n was found by calculating the vector $\mathbf{r}$ joining the n-2^{th} point P_{n-2} to the n-1^{th} point P_{n-1}. We then add $\mathbf{r}$ to the position vector of P_{n-1} to get the point $(\mathrm{P}_n)_0$. The line joining P_{n-1} to $(\mathrm{P}_n)_0$ was then rotated through $\pm 45^\circ$ about P_{n-1} to define a circular segment of arc S_n centered on $(\mathrm{P}_n)_0$. The total flux contained in a $3.0''$ diameter circular aperture was then computed for each point along S_n, and the point P_n chosen to be the point at which this flux is maximized. If we then define a distance between points (set to be $4.5''$; this is small enough to give an acceptable resolution), and two initial points (set to be the points at $\pm 2.25''$ due north of object N, where the arc is running north-south), the arc is then uniquely defined. Positive directions are clockwise, and the minimum and maximum distances on the ordinate axes correspond to the ends of the arc i.e. the places

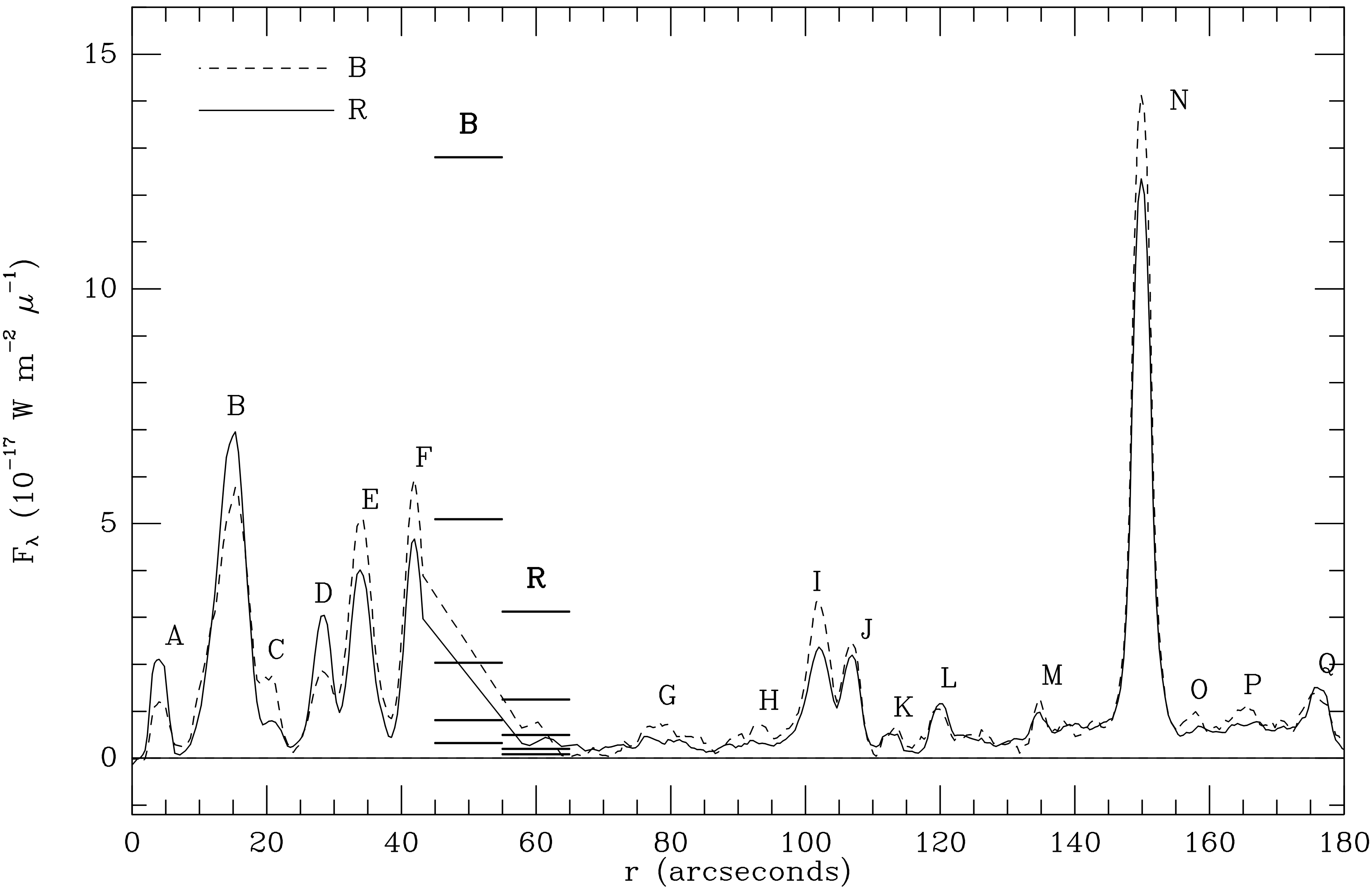
where the flux within a $3.0''$ diameter aperture drops to zero. The thick horizontal lines indicate average surface-brightnesses within the aperture of 24, 25, 26, 27, 28 mag arcsec^{-2}, from top to bottom in the B (left) and R (right) bands; **(b)** The location on the arc of the condensations described in the text and labelled in (a). The contours are from our B-band image (Figure 1(c)) and cover a 110 arcsecond square region with North up and East to the left. Some of the redder condensations appear only very faintly on this B-band image.

Table 1

Properties of objects within the arc

Object	m_B	α (1950)	δ (1950)	$B-R$	M_B (1)	Comments
A	24.46 ± 0.09	$12^h58^m2.22^s$	$28°19'22.49''$	2.17 ± 0.09	–	compact background galaxy
B	22.81 ± 0.02	$12^h58^m2.80^s$	$28°19'22.01''$	1.78 ± 0.02	-12.1	possibly background
C	24.06 ± 0.07	$12^h58^m3.19^s$	$28°19'18.81''$	0.72 ± 0.10	-10.8	
D	24.10 ± 0.07	$12^h58^m3.68^s$	$28°19'14.80''$	2.36 ± 0.07	–	compact background galaxy
E	22.89 ± 0.02	$12^h58^m4.10^s$	$28°19'15.00''$	1.27 ± 0.03	-12.0	
F	22.72 ± 0.02	$12^h58^m4.67^s$	$28°19'12.89''$	1.28 ± 0.02	-12.1	
G	25.12 ± 0.18	$12^h58^m5.71^s$	$28°19'13.41''$	0.72 ± 0.26	-9.8	diffuse fuzz
H	25.06 ± 0.17	$12^h58^m6.81^s$	$28°19'16.18''$	0.69 ± 0.25	-9.8	
I	23.31 ± 0.04	$12^h58^m7.40^s$	$28°19'20.34''$	1.14 ± 0.05	-11.6	
J	23.68 ± 0.05	$12^h58^m7.63^s$	$28°19'23.72''$	1.43 ± 0.06	-11.2	
K	25.27 ± 0.20	$12^h58^m8.01^s$	$28°19'26.98''$	1.42 ± 0.23	-9.6	
L	24.53 ± 0.11	$12^h58^m8.15^s$	$28°19'33.03''$	1.56 ± 0.12	-10.4	
M	24.28 ± 0.08	$12^h58^m8.65^s$	$28°19'44.88''$	2.23 ± 0.08	–	compact background galaxy
N	21.77 ± 0.01	$12^h58^m8.17^s$	$28°19'59.83''$	1.38 ± 0.01	-13.1	
O	24.82 ± 0.14	$12^h58^m8.34^s$	$28°20'7.28''$	1.02 ± 0.18	-10.1	
P	24.72 ± 0.12	$12^h58^m7.60^s$	$28°20'10.53''$	1.12 ± 0.15	-10.2	diffuse fuzz
Q1	24.66 ± 0.12	$12^h58^m7.51^s$	$28°20'19.19''$	1.55 ± 0.13	-10.2	
Q2	24.49 ± 0.10	$12^h58^m7.53^s$	$28°20'20.99''$	1.85 ± 0.11	-10.4	compact; possibly background

(1) Assuming that the object is in the Coma cluster, for which we adopt a distance modulus of 34.83.



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http://arXiv.org/ps/astro-ph/9708248v1

Table 2

Galaxies in the region of the arc

Galaxy	m_B	Type	V	α (1950)	δ (1950)	$B-R$
IC 4041	15.3	S0	7056	$12^{\rm h}58^{\rm m}16.1^{\rm s}$	$28°15'56''$	1.49
IC 4042	15.3	SB0	6363	$12^{\rm h}58^{\rm m}18.1^{\rm s}$	$28°14'25''$	1.59
IC 4040	15.4	Sdm	7850	$12^{\rm h}58^{\rm m}13.3^{\rm s}$	$28°19'35''$	1.10
IC 4026	15.6	SB0	8220	$12^{\rm h}57^{\rm m}57.4^{\rm s}$	$28°18'59''$	1.47
RB 110*	15.8	S0	7537	$12^{\rm h}58^{\rm m}14.1^{\rm s}$	$28°17'00''$	1.45
RB 100	16.2	S0	7679	$12^{\rm h}58^{\rm m}03.5^{\rm s}$	$28°14'29''$	1.45

The columns are: galaxy name (the RB numbers are from Rood & Baum 1967); blue magnitude m_B; galaxy morphological type; heliocentric radial velocity V; right ascension α; declination δ; $B-R$ color within a 3 arcsecond aperture centered on the galaxy.

The data in this table comes from the NASA/IPAC extragalactic database (NED), excepting the last column. The reader is referred there for the original sources.

*This galaxy has a small companion, RB 109 ($m_B = 18.9$, $B-R = 1.44$), 6.3 arcseconds to the northwest. No velocity measurements are available for the companion.